Laminar-Turbulent Transition Measurements in the Boeing/AFOSR Mach-6 Quiet Tunnel*

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Abstract

In September 2006, the Mach-6 tunnel at Purdue became quiet to stagnation pressures as high as 153 psia, yielding quiet freestream Reynolds numbers of more than 3×10^6/ft. It is the only operational hypersonic quiet tunnel in the world. The tunnel continued quiet in regular use through March 2007, when the performance degraded. In late April 2007, the compressor failed. After the compressor is replaced, the performance is to be restored by blowing out dust, cleaning the nozzle, or if necessary repolishing the nozzle. The design and fabrication of a new model-support section is also described; this new section is to enable running larger models with stronger bow shocks even when the nozzle-wall boundary layer is laminar.

Introduction

Hypersonic Laminar-Turbulent Transition

Laminar-turbulent transition in hypersonic boundary layers is important for prediction and control of heat transfer, skin friction, and other boundary layer properties. Vehicles that spend extended periods at hypersonic speeds may be critically affected by the uncertainties in transition prediction, depending on their Reynolds numbers. Although slender vehicles are the primary concern, blunt vehicles are also affected by transition [1]. However, the mechanisms leading to transition are still poorly understood, even in low-noise environments.

Many transition experiments have been carried out in conventional ground-testing facilities over the past 50 years [2]. However, these experiments are contaminated by the high levels of noise that radiate from the turbulent boundary layers normally present on the wind tunnel walls [3]. These noise levels, typically 0.5-1% of the mean, are an order of magnitude larger than those observed in flight [4, 5]. These high noise levels can cause transition to occur an order of magnitude earlier than in flight [3, 5]. In addition, the mechanisms of transition operational in small-disturbance environments can be changed or bypassed altogether in high-noise environments; these changes in the mechanisms change the parametric trends in transition [4]. Mechanism-based prediction methods must be developed, supported in part with measurements of the mechanisms in quiet wind tunnels.

Development of Quiet-Flow Wind Tunnels

Only in the last two decades have low-noise supersonic wind tunnels been developed [3, 6]. This development has been difficult, since the test-section wall boundary-layers must be kept laminar in order to avoid high levels of eddy-Mach-wave acoustic radiation from the normally-present turbulent boundary layers. A Mach-3.5 tunnel was the first to be successfully developed at NASA Langley [7]. Langley then developed a Mach-6 quiet nozzle, which was used as a starting point for the new Purdue nozzle [8]. Unfortunately, this nozzle was removed from service due to a space conflict; it is now being reinstalled at Texas A&M.

To provide high-Reynolds number quiet flow with affordable operating costs, the Purdue facility was designed as a Ludwieg tube [9]. A Ludwieg tube

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is a long pipe with a converging-diverging nozzle on the end, from which flow exits into the nozzle, test section, and second throat (Figure 1). A diaphragm is placed downstream of the test section. When the diaphragm bursts, an expansion wave travels upstream through the test section into the driver tube. Since the flow remains quiet after the wave reflects from the contraction, sufficient vacuum can extend the useful runtime to many cycles of expansion-wave reflection, during which the pressure drops quasi-statically.

The contraction-wall boundary layer is bled off just upstream of the throat, beginning a fresh undisturbed boundary layer for the nozzle wall. The nozzle-throat bleed air can be ducted to two alternate locations. A fast valve remains connected directly between the bleeds and the vacuum tank, allowing the bleed air to be dumped directly into the tank.

Figure 2 shows the nozzle exit. Here, z is an axial coordinate whose origin is at the nozzle throat. The region of useful quiet flow lies between the characteristics marking the onset of uniform flow, and the characteristics marking the upstream boundary of acoustic radiation from the onset of turbulence in the nozzle-wall boundary layer. A 7.5-deg. sharp cone is drawn on the figure. The rectangles are drawn on the nozzle at the location of window openings, all but one of which are presently filled with blank metal inserts. Images of the tunnel are available at `http://roger.ecn.purdue.edu/~aae519/BAM6QT-Mach-6-tunnel/`, along with earlier papers and other documentation. The Purdue Mach-6 tunnel is presently the only operational hypersonic quiet tunnel, anywhere in the world.

Nozzle Performance Since January 2007

Starting in mid-September 2006, the BAM6QT ran consistently with low noise levels ($\tilde{p}/\bar{p} < 0.05\%$) below a stagnation pressure that was typically near 145 psia. Quiet flow was achieved to stagnation pressures as high as 153 psia in fall 2006, but 145 psia was more typical. Here, $\tilde{p}/\bar{p}$ is the rms pitot fluctuations divided by the mean. For all runs the initial stagnation temperature was about 433 K.

Figure 3, reproduced from Ref. [10], shows sample data without a model in the tunnel, and a pitot sensor on the centerline 93.4 in. downstream of throat. The oscilloscope records data for ten seconds and is triggered by the sudden drop in pitot pressure when the diaphragms burst. The first second of data is from before the trigger, and provides a baseline of electronic noise. At time $t \simeq 0.0$ s, the diaphragms burst and the run starts. Approximately 0.2 s is required to start up the Mach-6 flow. During this run, the tunnel runs at a conventionally high noise level until $t \simeq 1.0$ s. At $t \simeq 1.0$ s the boundary layer on the nozzle wall drops from turbulent to intermittent, becoming laminar and quiet at $t \simeq 1.2$ s. The contraction-wall pressure is shown in blue and referred to the right-hand axis. It drops from an initial value of 160 psia in stair steps, each time the expansion wave reflects from the contraction. The contraction pressure at which the noise drops to quiet levels is about 146 psia. With the exception of five turbulent bursts between $t \simeq 2.8$ and 5.7 s, the tunnel is quiet until the run ends at $t \simeq 7.1$ s, when the contraction-wall pressure has dropped 28% to about 105 psia. The pressure at which the nozzle drops quiet is essentially independent of the time during the run at which this pressure is achieved.

It is critical to monitor the performance of quiet tunnels for every run, if possible, since it only requires a scratch or a speck of dust in the nozzle throat to eliminate quiet flow, and it is necessary to know if the measurements on a model during a particular run were obtained under quiet or noisy flow. Almost all previously-reported tunnel noise results have been from pitot-mounted pressure transducers with no model in the tunnel. However, a wall-mounted hot-film array is located in the test section, from $z = 74.25$ to 83.25 in. downstream of the throat [11]. The most frequently used hot film is that on the lower centerline at $z = 75.0$ in. It detects quiet, noisy, and separated flow as well as a pitot does, but without disturbing the flow around a model [12]. Thus, it is easily used to monitor flow quality. Typical results are shown in Fig. 4, where the run begins at $t \simeq 0.0$ s, followed by 0.2 s of start up. At $t \simeq 0.9$ s and $p_t \simeq 150$ psia the flow becomes quiet, and remains so until the end of the run at $t \simeq 7.2$ s. Note that the contraction pressure goes off scale and flat-lines near 102 psia although it actually continued to decrease. There are six large peaks during the quiet period that are the result of turbulent bursts that in principle could be observed with a centerline pitot; the other smaller spikes are lesser fluctuations that do not usually correlate with peaks on a centerline pitot when one is available [12].

Figure 5 illustrates the agreement between pitot pressure and wall-mounted hot-film traces. Unfortunately, the pitot pressure goes off-scale when the flow

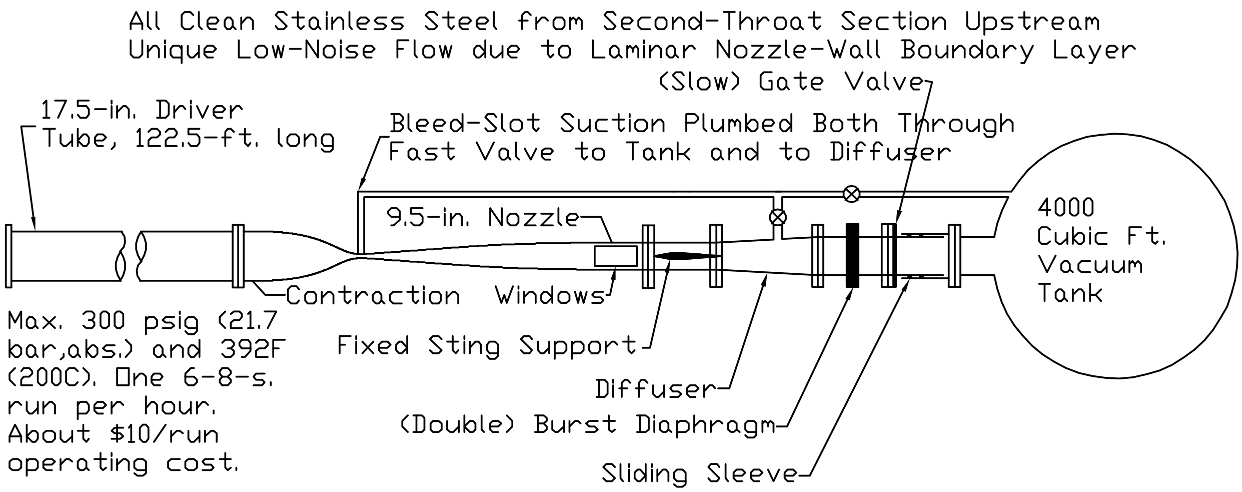

Figure 1: Schematic of Boeing/AFOSR Mach-6 Quiet Tunnel

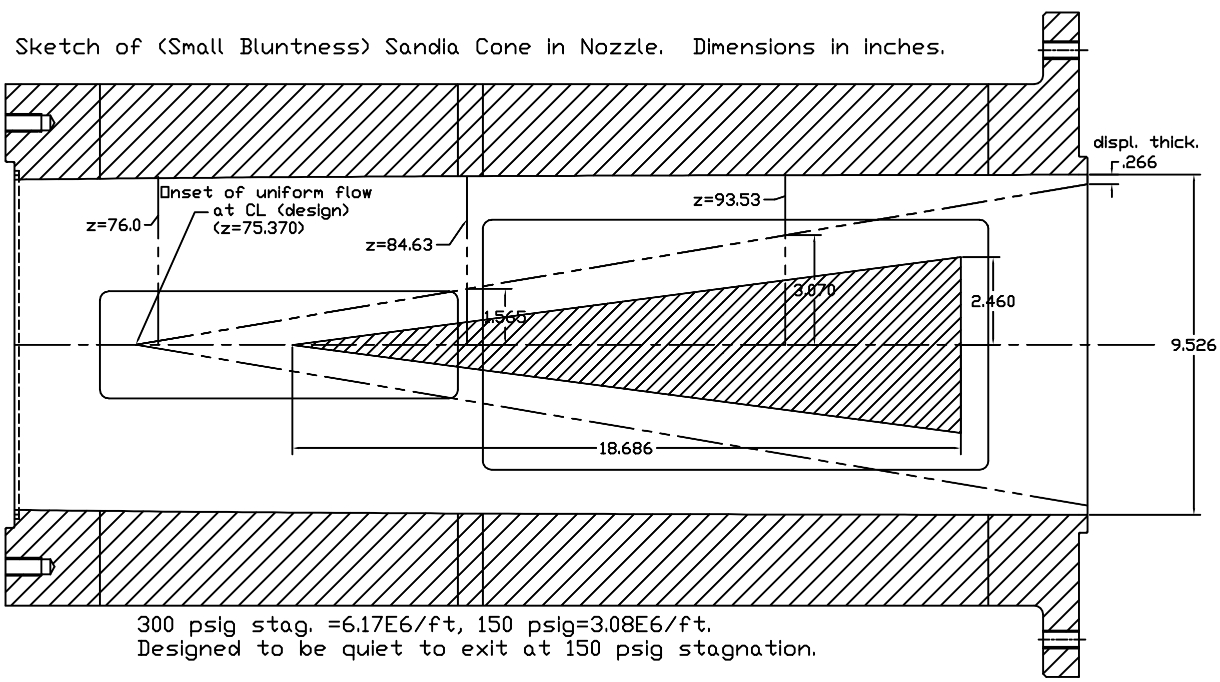

Figure 2: Schematic of Test Region of Mach-6 Quiet Nozzle with Model

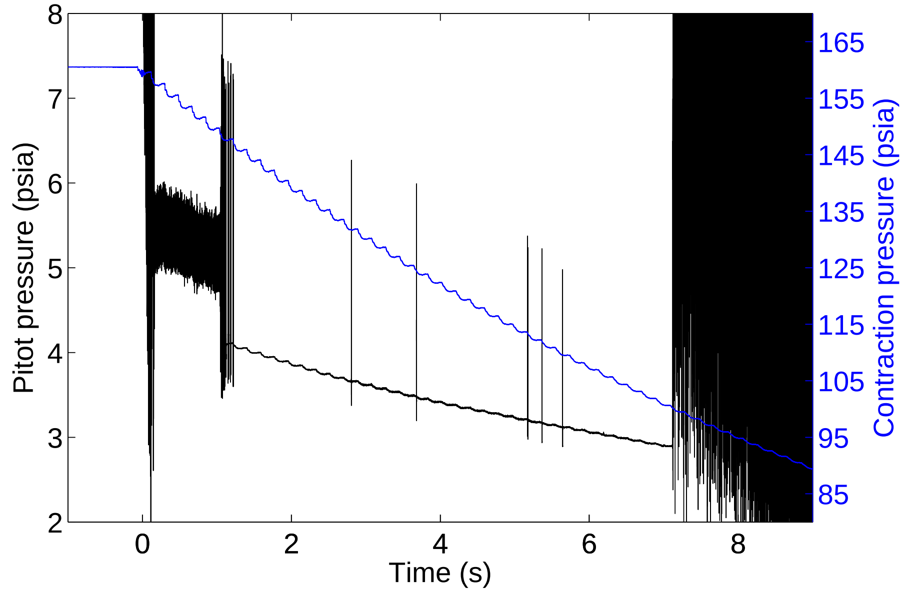

Figure 3: Pitot pressure showing quiet flow at high pressure (145 psia) with a few turbulent bursts

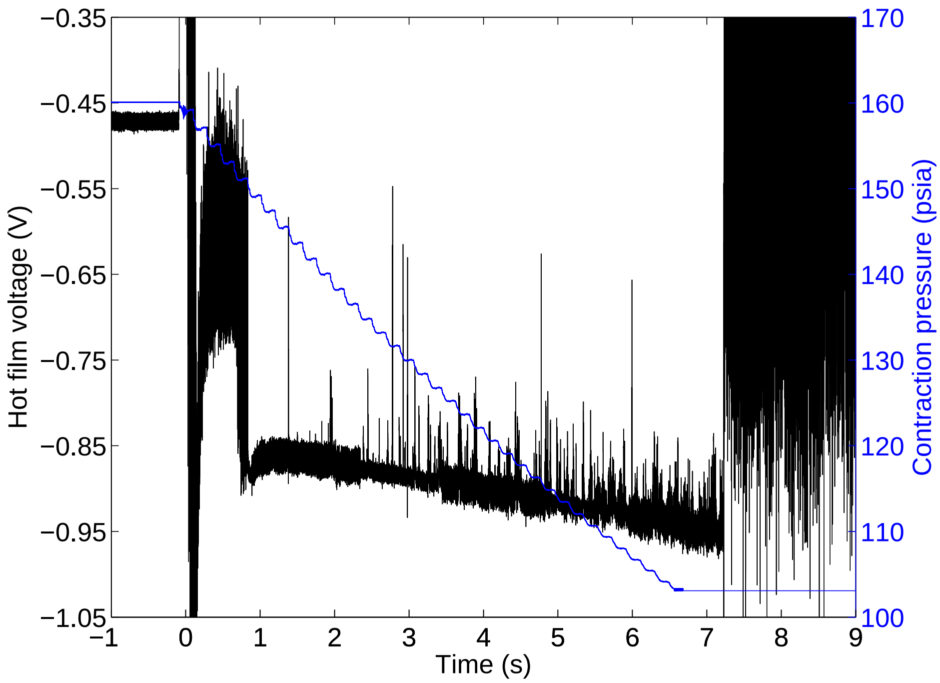

Figure 4: Wall-mounted hot-film trace showing quiet flow with six turbulent bursts

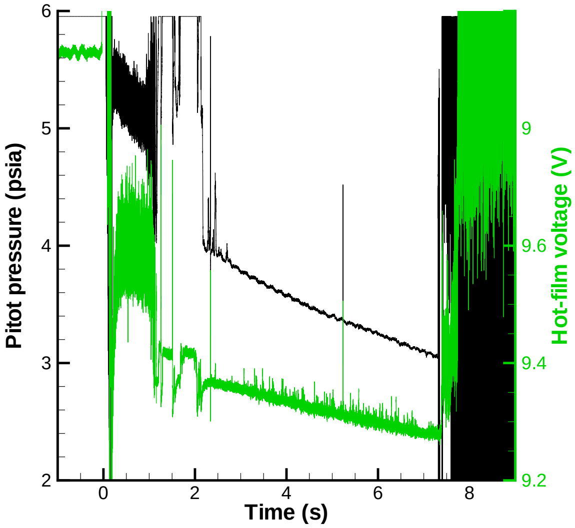

Figure 5: Comparison of signals from pitot sensor and wall-mounted hot-film

separates. Both traces show run start at $t \simeq 0.0$ s, noisy flow from 0.2 to 1.2 s, separation from 1.2 to 2.2 s, and turbulent bursts at 2.4 and 5.3 s. The hot film registers more noise and several smaller peaks. Only the largest peaks are turbulent bursts as identified by the pitot.

Hot-film data similar to Fig. 4 showed that the tunnel was still running quietly at high pressures through February 2007, with a similar number of turbulent spikes during the quiet portions of typical runs. In the six months from Sept. through Feb. the tunnel ran all but a couple of weeks, 5 to 6 days per week, as many as 10 runs per day. Quiet flow was reliably obtained with very little maintenance, and the throat was not opened.

During the first week of March 2007, the diaphragms were burst before opening the gate valve, which raised concerns about the nozzle performance. However, the wall-mounted hot-film array in the test section detected no decrease in quiet pressure. The number of turbulent bursts increased by a factor of perhaps 5 in subsequent runs, but this increase in the quantity of bursts was not very unusual for normal runs. Figure 6 shows typical data for a run in early March, with about 25 turbulent bursts visible. Since each burst lasts only a few ms, the effect on the mean flow remains small.

In early April 2007, the performance degraded more significantly. The maximum quiet pressure remained unchanged at 145 psia. However, when the initial stagnation pressure was less than the quiet pressure, there were many more turbulent bursts than before (Figure 7). When the initial stagnation pressure was greater than 145 psia, quiet flow was not achieved at all. Rather, there was an even higher frequency of turbulent bursts, on par with the intermittent turbulence heretofore seen only for about 0.2 s while the nozzle wall boundary layers were right on the edge between turbulent and laminar. Additionally, the flow switches from intermittently turbulent to fully turbulent after the stagnation pressure has dropped below 110 psia (Figure 8). It is unknown why a lower pressure would result in turbulent nozzle wall boundary layers.

The quiet pressure decreased in mid-April, ending six months of consistent quiet operation at high stagnation pressures above 145 psia. A new fast-acting valve was installed in the line between the throat bleeds and the vacuum tank. It is possible that the installation and testing introduced dust into the nozzle. Runs were conducted with no model and a pitot-mounted pressure transducer located in the test section 89.9 in. downstream of the throat. The quiet pressure dropped to 93 psia, its lowest value since August 2006. Not only has the quiet pressure decreased, but the quiet portion of the run exhibits numerous turbulent bursts, as shown in Fig. 9.

Figure 10 shows a detail of the many turbulent bursts during the still-mostly-quiet period. For $t = 4$ to 6 s, there is a turbulent burst detected by the pitot transducer 6% of the time. This value was calculated by constructing a histogram of the pitot pressure during the quiet portion of the run, as shown in Figure 11. The mean quiet pitot pressure ranges from 2.52 to 2.20 psia. The pressures outside of this range correspond roughly to the turbulent bursts.

It is possible that dust or other debris has deposited in the throat to reduce the quiet performance. It is also possible that the polish has degraded during ten months of frequent operation. Since the tunnel air compressor failed on 24 April, no runs could be made during May. Experiments are to resume when a new compressor arrives and is installed, perhaps in early June. Very high pressure ($p_t > 270$ psia) runs are planned in an effort to blow out any dust in the nozzle. If this fails to restore the quiet performance, the nozzle may be detached and cleaned. Previous experience with detaching and cleaning the throat yielded large variations in subsequent performance, perhaps due to dust introduced when the throat is opened. In the

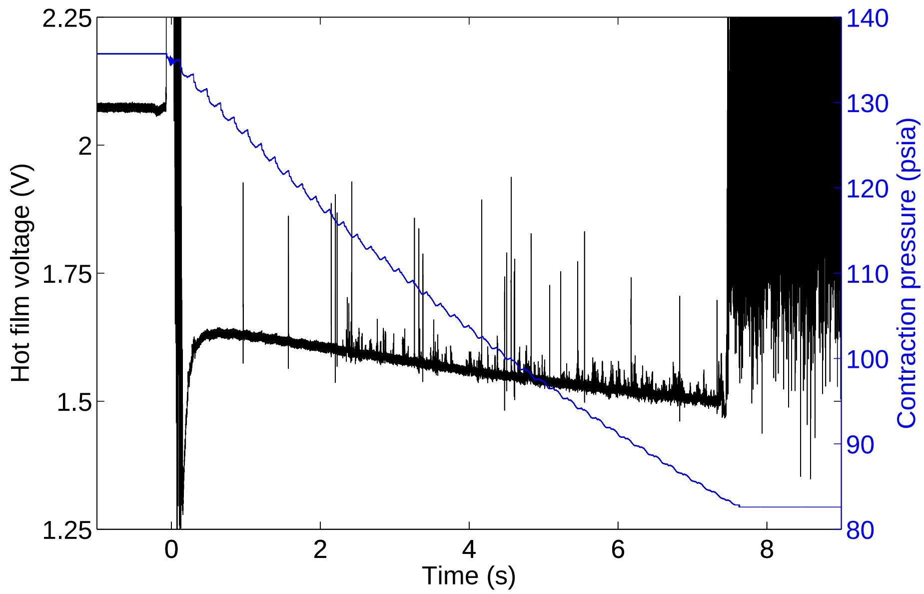

Figure 6: Wall-mounted hot-film trace showing quiet flow with more turbulent bursts

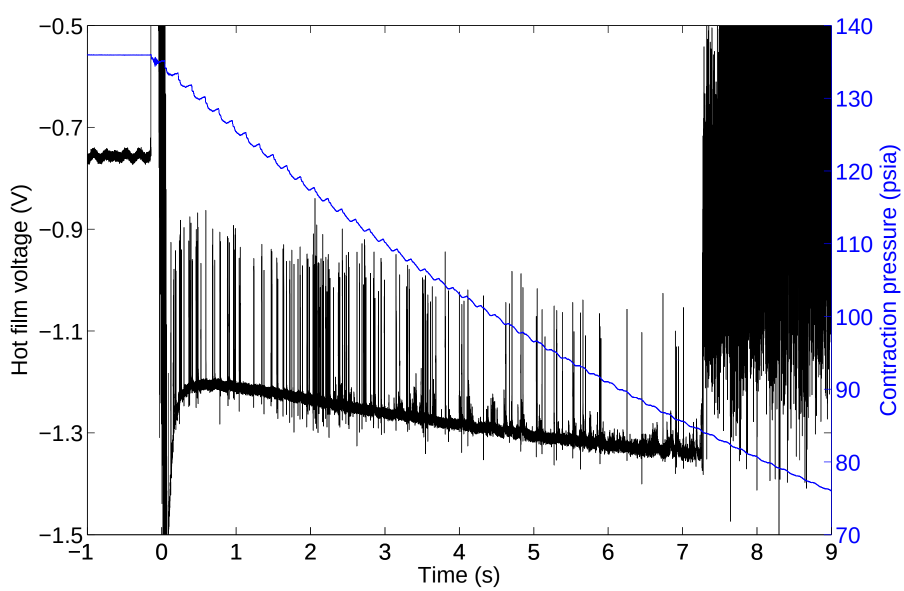

Figure 7: Wall-mounted hot-film trace showing large quantity of turbulent bursts

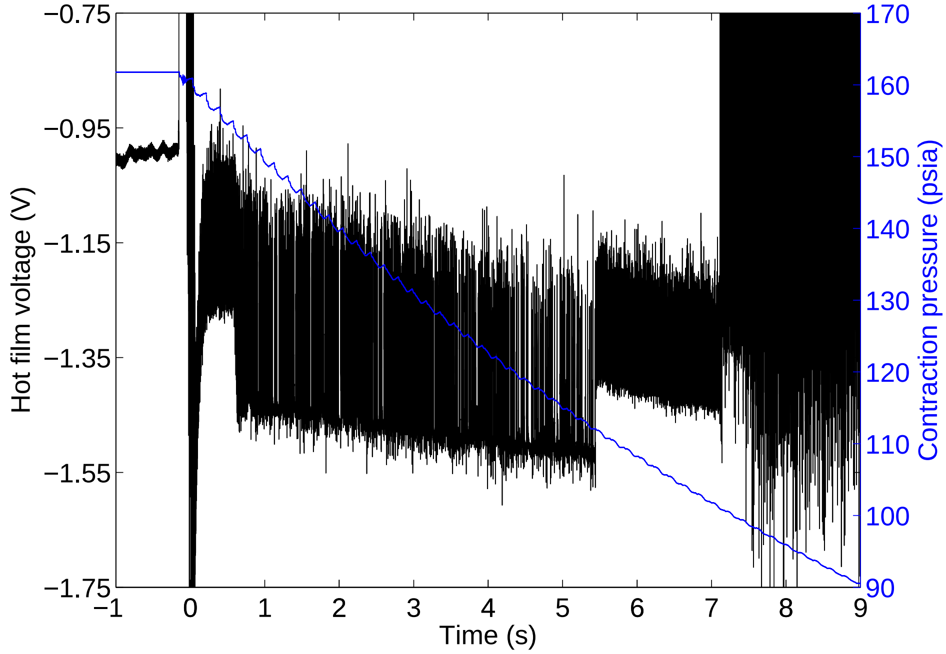

Figure 8: Wall-mounted hot-film trace showing noisy and intermittently-noisy flow

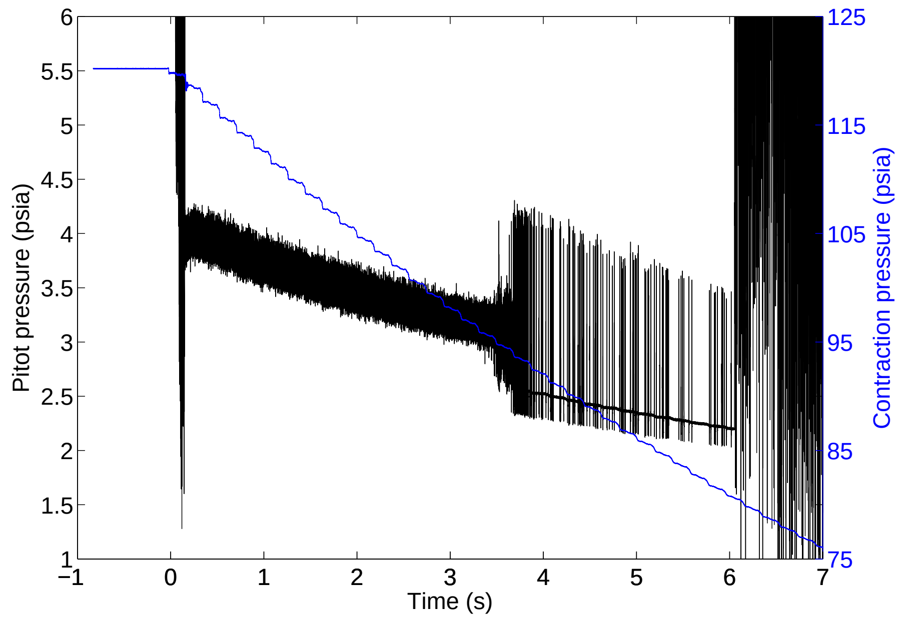

Figure 9: Pitot pressure trace showing quiet flow for $p_t < 93$ psia

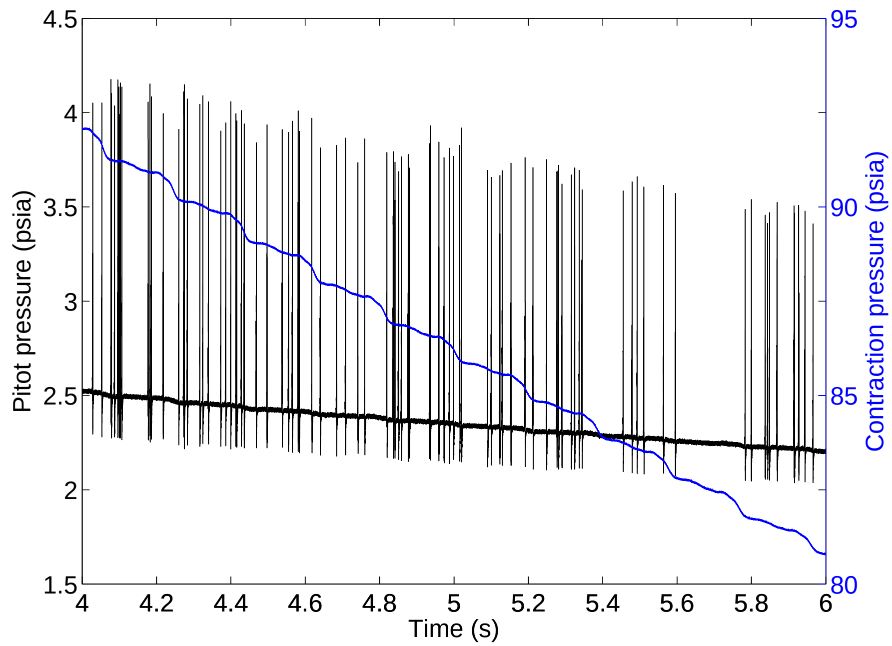

Figure 10: Pitot pressure during quiet portion of above run

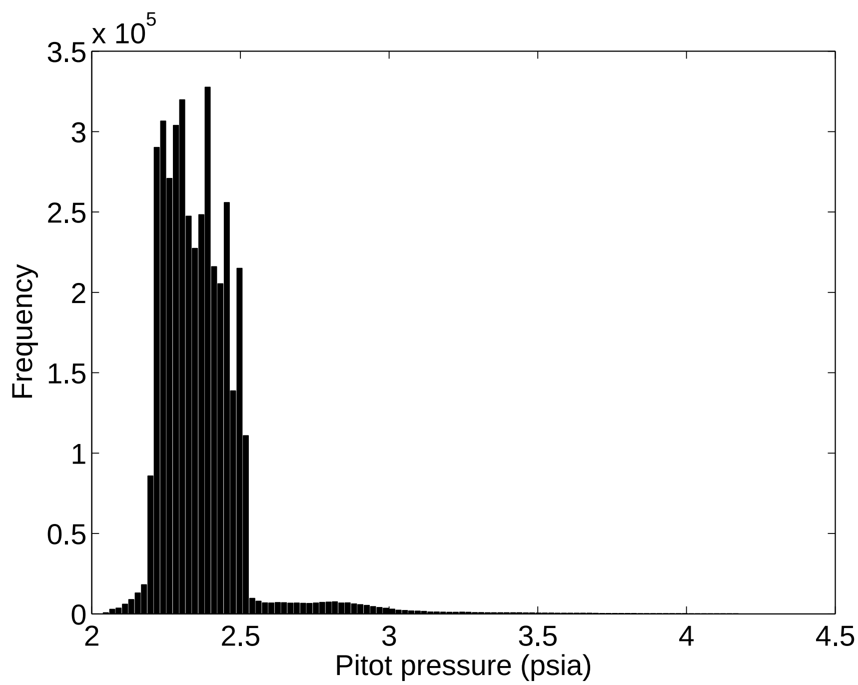

Figure 11: Pitot pressure distribution during quiet portion of above run

future, high-pressure runs are to be carried out immediately after such throat cleanings, in an attempt to blow out the dust that is necessarily introduced.

Design and Fabrication of New Sting-Support and Diffuser

A slender cone at zero angle of attack has successfully started in the quiet tunnel for a base diameter of 5.5 inches [13]. However, models with strong bow shocks must be much smaller to avoid separation induced by shock/boundary-layer interaction at the nozzle wall [14, pp. 36-39]. For example, a 70-deg. swept slab delta model could not be started at 40-deg. angle of attack even when only 4 inches long [13]. Nevertheless, Hornung et al. have successfully started a 7-in.-dia. blunt planetary probe in a shock-tunnel nozzle with a 12-in. diameter that flows directly into a vacuum dump tank [15]. Quiet tunnels might be expected to unstart with weaker bow shocks, since the laminar nozzle-wall boundary layers often present even at the nozzle exit are less resistant to separation.

Thus, there is a complex interaction between the nozzle-wall boundary layer and the model bow shock that can propagate upstream in the boundary layer and induce separation. Controlling this poorly-understood interaction is critical to starting larger blunt models for high-Reynolds-number quiet-flow experiments related to transition on capsules and the Space Shuttle. In accordance with suggestions by Craig Skoch [16] and by Lex Smits of Princeton, it seems likely that larger blunt models will start if the bow shock impinges on a shear layer aft of the nozzle, rather than on the nozzle-wall boundary layer. This might explain why Hornung's shock-tunnel experiments could use such a large model.

The sting-support section is therefore being replaced with a new one of larger diameter, so the nozzle exhausts past a backward facing step, as is shown in Fig. 12. Flow enters this section from the end of the nozzle at the left-hand side, passing over a 45-deg. expansion from 9.526-in. diameter to 14-1/8-in. diameter. The nozzle-wall boundary layer is expected to separate into a shear layer at the expansion corner, and then reattach at some point downstream. Preliminary computations supporting the concept are reported in Ref. [17].

A schematic of an Apollo model at angle of attack is shown in red, along with a crude representation of the bow shock. The thin-blade sting-support section is shown in blue – the design is patterned after that shown in Ref. [18, pp. 9-10]. The shock from the model is to impinge on the shear layer aft of the step, which seems likely to reduce the upstream propagation of disturbances, and the separation of the upstream boundary layer which results for excessively strong bow shocks.

To start large models anywhere near the diameters started in the shock tunnel, it will be necessary to effectively remove the gas on the outer side of the shear layer. Although the performance of a direct entry into the dump tank cannot be matched, the 14-1/8-in. exit diameter is being maintained through the 36-inch length of the sting-support section. Fig. 13 shows that this section includes provisions for a pair of small rectangular windows below the centerline, a pair of slots permitting later insertion of probes, a series of pressure-tap holes along the walls, and a 6-inch port for accessing the wiring behind models.

Downstream of the new sting-support section, this 14-1/8-in. diameter is slowly reduced to the 12-in. diameter of the existing burst-diaphragm section using a new diffuser. The new diffuser has a very small 0.9-deg. taper along its 72-inch length. This gradual compression appears likely to produce the least amount of boundary-layer separation.

Unlike the existing diffuser, which begins at the 9-1/2-in. diam. of the nozzle exit, expands to 12-in. diam., and permits the entry of the bleed flow from the nozzle throat, the new diffuser has no provision for reentry of the 38% massflow from the throat bleeds. Instead, a new fast 4-inch valve has been installed on the 4-inch vacuum line that is plumbed directly to the vacuum tank. Once the new system is installed, the bleed air from the throat can no longer flow into the diffuser with passive timing, but only directly into the vacuum tank. When the burst diaphragm breaks, the pressure will drop in the test section, and this signal will be used to open the fast valve in the bleed line.

The new fast 4-inch valve has already been installed, after completion of preliminary tests. Bench tests show that it opens in less than 1/30 s, powered by a 120 psi external air supply. The new sting-support and diffuser sections are to be completed in June. The system should be installed in the tunnel over the summer, and its performance is to be tested during the fall.

Summary

The Boeing/AFOSR Mach-6 Quiet Tunnel continued to achieve quiet flow at Reynolds numbers above

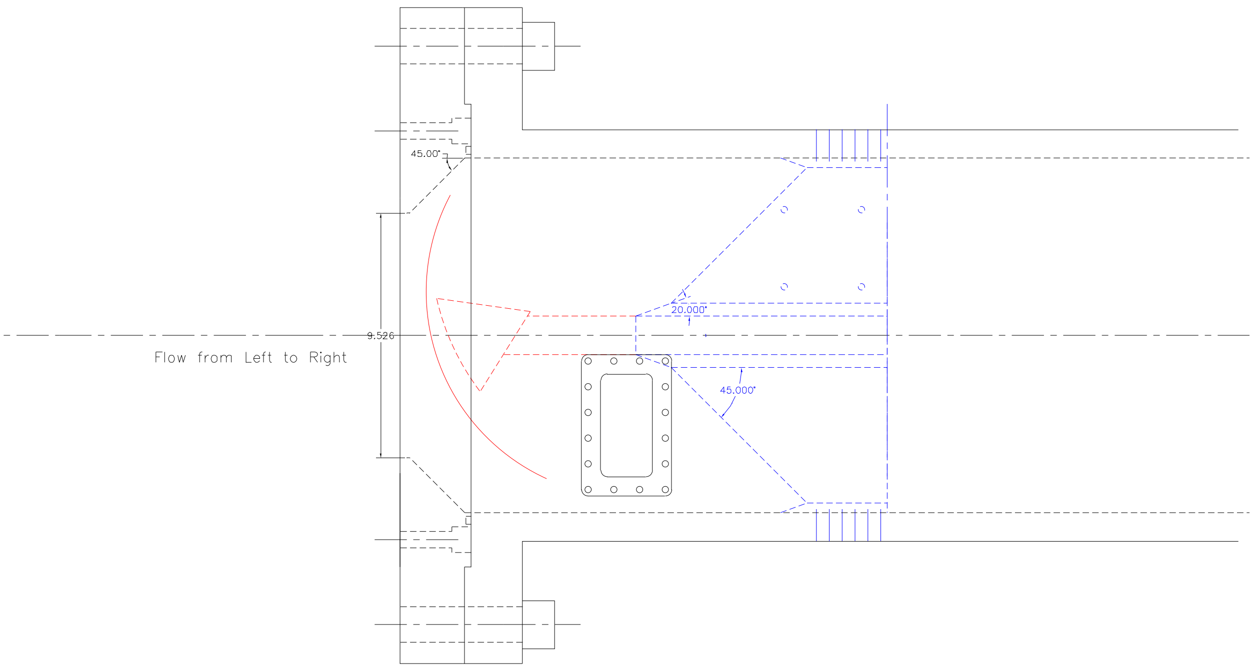

Figure 12: Schematic of New Sting-Support Section with Semi-Open Jet Configuration

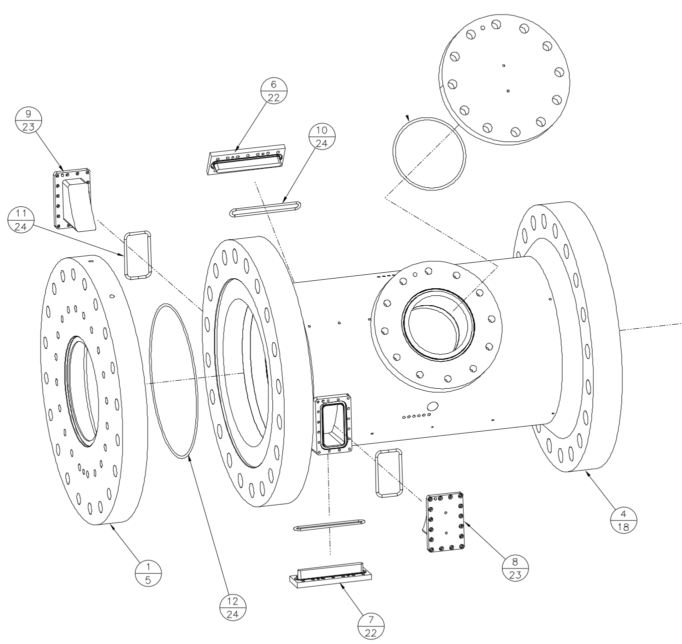

Figure 13: Drawing of New Sting-Support Section

3 million per foot from Sept. 2006 through Feb. 2007, with little maintenance. During this 6-month period, the tunnel ran 5-6 days per week for all but two of the weeks, for as many as 10 runs per day, and the throat section was never opened. Beginning in March 2007, the quiet flow performance began to degrade, perhaps due to the deposit of dust or other debris in the throat, or perhaps due to the degradation of the throat finish. The 50HP air compressor failed in late April, precluding further experiments. After a new compressor is installed in early June, high pressure runs will be made to blow out dust from the throat. If these are unsuccessful in restoring performance, the throat will be opened for cleaning. If necessary, the throat section is to be repolished.

In order to start larger blunt models under quiet conditions, the portion of the tunnel between the nozzle exit and the burst-diaphragm section is being replaced. An aft-facing step downstream of the 9-1/2-in.-dia. nozzle exit will increase the flow diameter to 14-1/8 in. for some 36 inches, after which the diameter will taper down at a 0.9-deg. angle to meet the 12-in.-dia. burst-diaphragm section. The bleed air from the nozzle throat will be plumbed directly to the vacuum tank and not to the diffuser. When the bow shocks from the models impinge on the free shear layer aft of the nozzle exit, the resulting viscous interactions appear less likely to propagate upstream and separate the nozzle-wall boundary layer.

Acknowledgements

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